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EXPERMENTAL RESULTS FOR A PHOTONIC TIME REVERSAL PROCESSOR FOR ADAPTIVE CONTROL OF AN ULTRA WIDEBAND PHASED ARRAY ANTENNA

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ABSTRACT

This paper describes a new concept for a photonic implementation of a time reversed RF antenna array beamforming system. The process does not require analog to digital conversion to implement and is therefore particularly suited for high bandwidth applications. Significantly, propagation distortion due to atmospheric effects, clutter, etc. is automatically accounted for with the time reversal process. The approach utilizes the reflection of an initial interrogation signal from off an extended target to precisely time match the radiating elements of the array so as to re-radiate signals precisely back to the target's location. The backscattered signal(s) from the desired location is captured by each antenna and used to modulate a pulsed laser. An electrooptic switch acts as a time gate to eliminate any unwanted signals such as those reflected from other targets whose range is different from that of the desired location resulting in a spatial null at that location. A chromatic dispersion processor is used to extract the exact array parameters of the received signal location. Hence, other than an approximate knowledge of the steering direction needed only to approximately establish the time gating, no knowledge of the target position is required, and hence no knowledge of the array element time delay is required. Target motion and/or array element jitter is automatically accounted for. Presented here are experimental results that demonstrate the ability of a photonic processor to perform the time-reversal operation on ultra-short electronic pulses.

KEYWORDS: Microwave Photonics, Adaptive Beamforming, Phased Array Antennas, Time Reversal, Ultra Wideband Radar

1 INTRODUCTION

1.1 Photonic Processing for Microwave Phased Array Antennas

It has been well established that optical signal processing methods provide the antenna array designer with unique capabilities generally not available using conventional microwave techniques. When compared with an all-microwave approach, the utilization of optical components, especially the incorporation of low loss optical fiber, can provide significant reduction in the size and weight of the system as well as providing a high degree of immunity to electromagnetic interference (EMI) and electromagnetic pulse (EMP) effects making them attractive for use with secure communications and in electromagnetically rich environments. More importantly, however, the extremely broad microwave bandwidth generally associated with photonic systems allows for antenna control and processing with RF/microwave bandwidths that are unobtainable

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using all-microwave processing. Furthermore, although Digital Signal Processing (DSP) provides a powerful tool when applied to array signal processing, bandwidth limitations on the Analog-to-Digital Converter (ADC) and algorithm processing time can introduce limitations to DSP applicability for extremely broadband systems. Once again, the inherently broad bandwidth of microwave photonics along with its associated high processing speeds helps to mitigate these problems [1, 2, 3].

Time Reversal, a process well-known in the sonar community, is an adaptive array process based on the premise that if one can reverse a signal $f(t)$, that is, generate $f(-t)$, then the signal can in principle be traced back to its source [5]. This is particularly useful in many RF antenna array applications since the information contained in the time reversed signal includes any irregularities in the path of propagation, i.e., index variations in a random atmosphere, beam diffraction due to propagation in inhomogeneous (e.g., layered) media, multiple scattering due to clutter or additional targets, and so forth. This information in turn allows for the automatic determination of the array element time delay needed to steer the aperture back on to the target from which the signal originated. Normally the required time reversal signal processing would be performed by a digital signal processing system (DSP) [6, 7]. However, for those instances where the operational bandwidth is so large that a suitably fast analog-to-digital converter (ADC) does not exist, a photonic can be used to perform the time reversal in the optical domain.

2 THEORY OF OPERATION

2.1 Conventional Phased Arrays

Most optical beamforming systems extant fall into one of two categories; delay-and-sum beamforming and Fourier-based beamforming. From a target tracking point of view, problems posed by these systems include a-priori knowledge of the exact position of where one wishes to steer the array, precisely specified stable antenna array locations, difficulty in specifying and generating antenna nulls to counteract the effect of interference, and the inability to easily account for atmospheric effects.

2.2 Time Reversal

The time reversal process has long been of interest to the sonar community and applications similar to those discussed in this paper have been explored in the literature under the title of "time lens" [8]. Its applicability to the present discussion is based on the reciprocal nature of the wave equation. In essence, a signal $f(t)$ is passed through a system with an output of $f(-t+T)$, the delay T being necessary to ensure that the signal remains causal. This effect can be realized using a photonic system, as will be explained in Section 3.2. Supposing that the signal $f(t)$ is the retro-reflected signal from a distant target, the time-reversed $f(-t+T)$ signal, when re-transmitted through the radar system, will serve as a precise true-time delay beam forming system. Thus the re-transmitted energy is focused by means of time reversal and a "time lens" is achieved. This concept has been employed with great success for the treatment of cancer using microwave hyperthermia with array apertures and time reversed signal processing, but at bandwidths significantly lower than those discussed in this paper [9].

2.3 Time Reversed Adaptive Array

The N radiating elements which form the time reversed array processor are conveniently placed in (fixed) locations or perhaps even mounted on a mobile platform. Variation in element location is automatically accounted for in the time reversal process. Once the existence and approximate location of the target has been ascertained the adaptive process proceeds as follows:

- An interrogation pulse is transmitted from any one array element (Figure 1a).
- All antennas are first set to operate in the receive mode.
- The backscattered signal is captured by each antenna. (Figure 1b)
- A time gate is employed to excise any unwanted reflections such as targets whose range is different from that of the desired target.
- When the back scattered signals are time reversed and re-radiated, the energies arrive at the target simultaneously maximizing the target fluence. (Figure 1c)

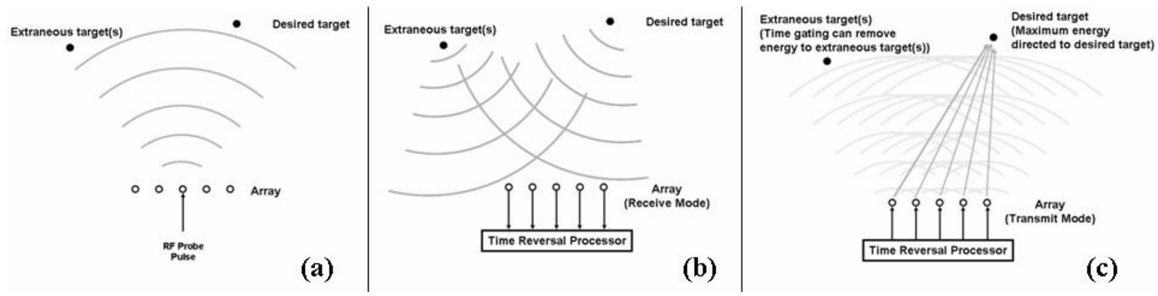

Figure 1: Sequence of events to implement time reversal. (a) An interrogation signal is transmitted from one antenna element. (b) The interrogation signal is scattered from the target(s) and received by all the array elements. (c) A time reversal processor is used to time gate the received signal, time reverse them, and amplify then retransmit these signals resulting in maximum target fluence.

3 PHOTONIC-BASED IMPLEMENTATION

3.1 Photonic Time Reversal Unit

The realization of the time reveal process using all-optical processing is illustrated in Figure 2. A laser pulse with optical spectrum $\Delta\lambda$ propagates in a dispersive medium. This dispersive medium can be a simple as a length of single mode optical fiber which has dispersion typically on the order of -20 picoseconds/(nanometer-kilometer) [11, 12]. Other dispersive elements can also be used, such as high chromatic dispersion optical fiber or a chirped fiber Bragg grating [13]. The length of the fiber is designed such that over the operational optical bandwidth $\Delta\lambda$, the time duration of the chirp signal is equal at least to duration of the modulating RF signal. The chirped or time stretched optical signal is modulated via a broadband electrooptic modulator by the RF/Microwave signal which is to be time reversed.

This RF modulated optical signal which is also temporally dispersed in wavelength is now directed to a second dispersive element whose dispersion slope is negative to that of the first dispersive element. This is accomplished for example by using a correctly oriented chirped Bragg grating. The signal which reflects from this second dispersive element will have the property that the long wavelength will be reflected first and the short wavelength last, opposite to what the first dispersive element produced. At this point, the RF signal which modulates the chirped optical carrier is now time reversed as the figure shows. A fixed amount of excess time delay is included to provide any necessary delay biasing for the array. A broadband photodetector is used to recover the time reversed RF signal for retransmission in the adaptive array system.

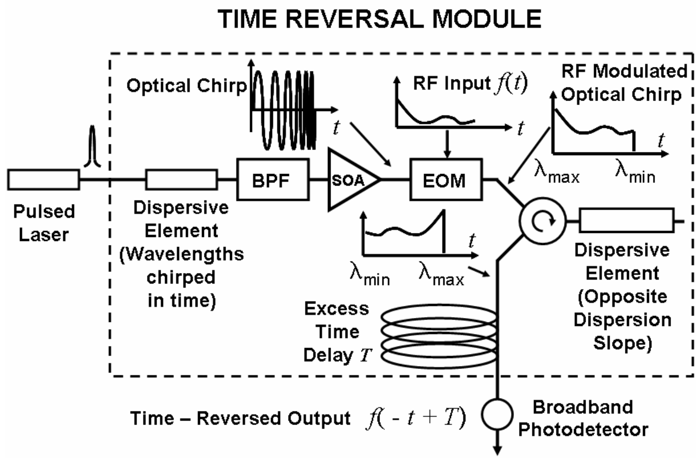

Figure 2: Optical system to implement RF time reversal.

3.2 Experimental Results

Figure 3 shows the experimental results for the Time Reversal Processor shown in Figure 2. Figure 3 (a) specifically illustrates the chirped optical signal modulated by an asymmetric doublet. This corresponds to the signal exiting the electrooptic modulator (EOM) of Figure 2. To illustrate the dynamics of time reversal, three distinct stages of the process will be shown. To achieve a time reversed version of the input signal a length of optical fiber equaling three kilometers is needed to produce a dispersion slope twice that and opposite to the Chirped Bragg Grating (CBG) used to produce the initial dispersion. Figure 3b shows the position of the doublet after propagation through one kilometer of fiber. It is seen that the two pulses which comprise the double have moved closer together in time. Figure 3c shows the doublet after propagating through two kilometers of fiber. It is now seen that the two distinct pulses that comprise the doublet are collocated in time. Finally, Figure 3d shows the doublet after propagation through the full three kilometers of fiber. Clearly the orientation of the pulses has switched.

3.3 Photonic Time Reversal-Based Phased Array Antenna

Figure 4 illustrates a block diagram showing the implementation of an adaptive antenna array using the time reversal process. To reduce the total number of components note that the time reversal module shown is slightly different from the one discussed in Section 3.2 in that the pulsed laser and first dispersive element, the SOA and optical bandpass filter are all now external to the module. For the array application, a single pulse laser of sufficient intensity to feed all the array elements is used along with one dispersive element. The optically chirped signal exiting the dispersive element is then directed to a 1 × N optical splitter, with the splitter outputs sent to one element of an N-element array.

Each antenna has a Transmit/Receive (T/R) module so that the elements can operate in the appropriate mode as discussed in Section 2.3 as well as a Low Noise Amplifier (LNA). The output of each timer reversal module, before photodetection, is sent to an electrooptic (EO) modulator which acts as the time gate to remove unwanted reflections. This gated signal is now photodetected and sent to the T/R module which is now set in the transmit mode for re-radiation of the time reversed signal.

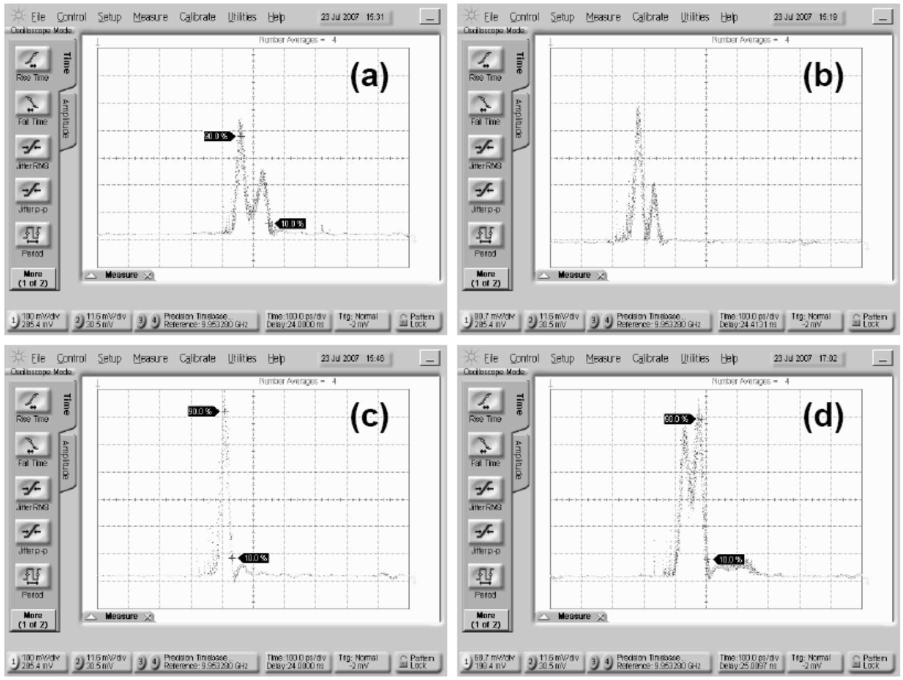

Figure 3: Experimental results. (a) doublet at the output of the chirped Bragg grating, and doublet after propagating through an optical fiber of length (b) 1 Km, (c) 2 Km, and (d) 3 Km.

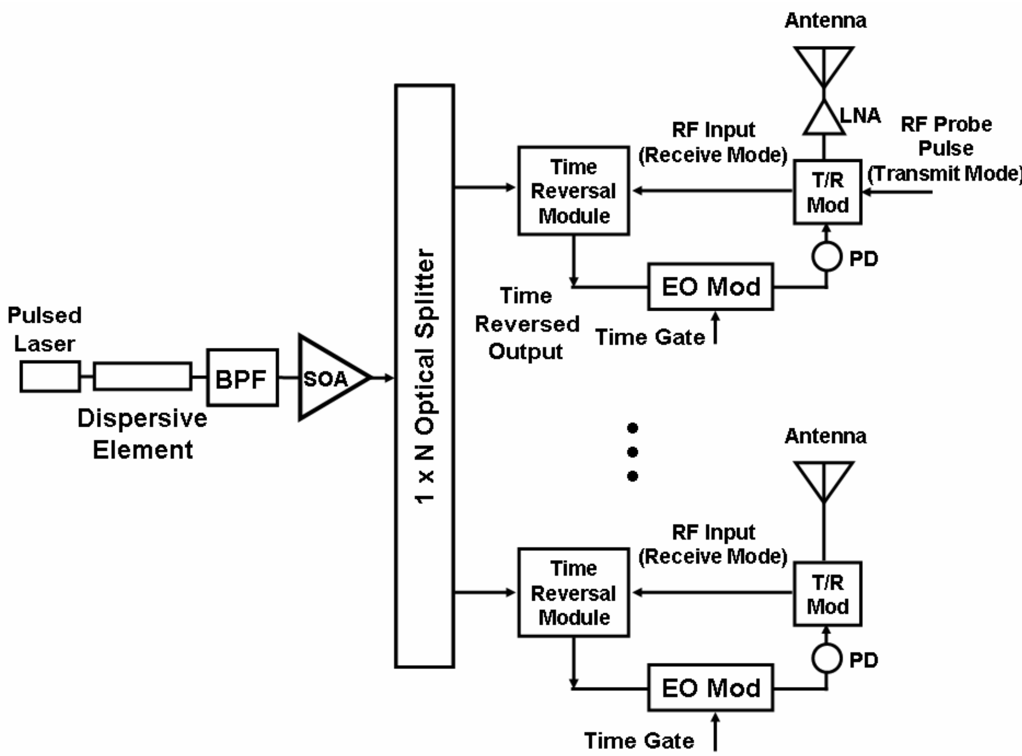

Figure 4: Block diagram for the photonic implementation of a time reversal-based antenna array.

4 CONCLUSIONS

4.1 Summary

A new approach for the design of an adaptive phased array antenna system has been presented. The approach makes use of the mathematical concept of time reversal which, because of the reciprocal nature of the wave equation can be used to accurately steer the array aperture so as to achieve maximal fluence on a given target. The time-domain nature of the approach also allows for the accurate placement of array null at specific spatial locations. This is achieved by using a time gate to excise those parts of the re-radiated signal that correspond to energy originally reflected from the null location. A particularly attractive aspect of the present approach is that the process automatically compensates for propagation effects in an inhomogeneous atmosphere. Also, an exact knowledge or placement of array element location is not required, and effects of target and/or motion and element jitter are accounted for. These characteristics thus represent a significant advantage over other conventional array beamforming techniques.

Though at lower bandwidths the processing is arguably best performed in the digital domain, presented here was an all-optical or photonic implementation which allows for the approach to be implemented for extremely broad bandwidth pulses. Extremely narrow pulses are useful in achieving high spatial resolution. The photonic system thus finds its greatest usefulness in systems where current ADC technology cannot meet the speed and resolution requirements needed.

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